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Tillage and wind effects on soil CO_2 concentrations in muck soils

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Abstract

Rising atmospheric carbon dioxide (CO_2) concentrations from agricultural activities prompted the need to quantify greenhouse gas emissions to better understand carbon (C) cycling and its role in environmental quality. The specific objective of this work was to determine the effect of no-tillage, deep plowing and wind speeds on the soil CO_2 concentration in muck (organic) soils of the Florida Everglades. Miniature infrared gas analyzers were installed at 30 cm and recorded every 15 min in muck soil plowed with the Harrell Switch Plow (HSP) to 41 cm and in soil Not Tilled (NT), i.e., not plowed in last 9 months. The soil CO_2 concentration exhibited temporal dynamics independent of barometric pressure fluctuations. Loosening the soil resulted in a very rapid decline in CO_2 concentration as a result of ''wind-induced'' gas exchange from the soil surface. Higher wind speeds during mid-day resulted in a more rapid loss of CO_2 from the HSP than from the NT plots. The subtle trend in the NT plots was similar, but lower in magnitude. Tillage-induced change in soil air porosity enabled wind speed to affect the gas exchange and soil CO_2 concentration at 30 cm, literally drawing the CO_2 out of the soil resulting in a rapid decline in the CO_2 concentration, indicating more rapid soil carbon loss with tillage. At the end of the study, CO_2 concentrations in the NT plots averaged about 3.3% while that in the plowed plots was about 1.4%. Wind and associated aerodynamic pressure fluctuations affect gas exchange from soils, especially tilled muck soils with low bulk densities and high soil air porosity following tillage.
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Keywords: Organic soils; Soil subsidence; Carbon dioxide fluxes; Soil carbon; Aerodynamic pressure effects; Soil air porosity

1. Introduction

The increasing importance of global climate change issues reflects the need for direct measurements to quantify greenhouse gas emissions, especially carbon dioxide (CO_2), influenced by agricultural management practices (Houghton et al., 1983; Schlesinger, 1985). Understanding these processes will lead to enhanced soil management techniques and new technology for increased food production efficiency with a minimum impact on environmental quality and greenhouse gas emissions (Paustian et al., 1997; Lal et al., 1998). Studies involving tillage methods indicate major gaseous losses of carbon (C) immediately after tillage (Ellert and Janzen, 1999; Reicosky and Lindstrom, 1993; Rochette and Angers, 1999). The interaction of

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combined meteorological and tillage impacts on soil gas fluxes is creating a new awareness of agricultural impacts.

Diffusion has long been considered the dominant process by which trace gases moved from the subsurface source to the soil surface; however, there has been indication that atmospheric pressure fluctuations also might play a role (Kimball, 1983; Nazaroff, 1992; Clarke and Waddington, 1991; Massman et al., 1997; Auer et al., 1996). Takle et al. (2003) measured CO_2 fluxes from the soil surface under conditions of natural and artificial pressure pumping at the soil surface. They showed that pressure changes due to fluctuations in wind speed and direction, interacting with a wind barrier, penetrated to at least 60 cm in bare, nearly dry clay loam soil. Takle et al. (2003) found that the CO_2 fluxes at the surface to be approximately three times as large as would be expected from calculations based on diffusional flux rates, in agreement with Kimball (1973). There is a strong suggestion that diffusion alone is not sufficient to explain the flux of CO_2 from the soil surface, but that increasing the magnitude of the pressure fluctuations will enhance soil CO_2 flux.

Wind and pressure forces were first identified as important determinants of the rate of gas exchange from the tilled soil surface by F.H. King (1891) as cited in Tanner and Simonson (1993). The influence of wind on soil water evaporation has been studied extensively (Hanks and Woodruff, 1958; Benoit and Kirkham, 1963; Scotter and Raats, 1969; Farrell et al., 1966). Increased wind speed increases water vapor transfer from soil through gravel and straw mulches, and is somewhat less effective in vapor transfer through soil mulches. Kimball and Lemon (1971) provided early insights about the effect of wind speed on heptane evaporation and exchange from the soil surface. They concluded that air turbulence increased the transport of water vapor through coarse mulches or through very shallow depths of soil. Kanemasu et al. (1974) and Kimball and Lemon (1971, 1972) showed that pressure deficits of 1 Pa resulted in significant mass flow from soils. The importance of mass flow induced by pressure deficits can be evaluated by determining if the flux from the soil differs for different flow rates of gas through a dynamic chamber as observed by Hanson et al. (1993). Varying the speed of the chamber-mixing fan showed that increased wind speeds up to 0.6 m s^{-1} inside the chamber can enhance the measured flux. They attributed this effect to the disruption of the normal high boundary layer by excessive turbulence. Denmead (1979) used a much smaller-scale chamber for measuring trace gases; a pressure deficit of 100 Pa caused a 10-fold increase in measured N_2O emissions.

Wind and associated pressure effects must always be considered in studies of soil gas exchange. The meteorological techniques for measuring CO_2 fluxes require a critical assumption of mass airflow to analyze high frequency wind fluctuations to quantify turbulent transport (Baldochi et al., 1988). Evidence suggests that convection can contribute, in certain circumstances following intensive tillage, to gas exchange and soil aeration, particularly at shallow depths and in soils with tillage-induced large pores (Renault et al., 1998). Kanemasu et al. (1974), Nakayama and Kimball (1988) and Nakayama (1990) showed that ‘‘blowing’’ air (positive air pressure) through a chamber gives flux results very different than ‘‘sucking’’ the air (negative air pressure) through the same chamber over the same soil. Nakayama and Kimball (1988) showed a 50–80% reduction in soil CO_2 flux at pressures in the range of 1–4 Pa above ambient. Apparently, the aerodynamic forces that yield net positive or negative pressures will affect the magnitude of the flux based on the wind speed and direction. The tillage-induced change in soil air porosity showed that convection contributes to gas exchange (Reicosky and Lindstrom, 1993).

Soil subsidence and C loss have become concerns for soil resources in the Florida Everglades sugarcane (*Saccharum* ssp.) area as a result of depleting muck (organic) soils. The relationship between land subsidence and drainage of wetland or marsh lands has been studied, but work has concentrated on laboratory measurements. In the laboratory, soil CO_2 evolution increased with temperature (between 10 °C and 60 °C) and soil organic C content, but decreased with increasing moisture content (Knipling et al., 1970; Volk, 1973; Tate, 1979, 1980a, 1980b). The rate of CO_2 evolution in the laboratory, a measure of soil C loss, agreed qualitatively with the rates of field measured subsidence and this suggests most subsidence in the Florida organic soils was a result of biochemical oxidation (Stevens and Stewart, 1976). Direct field measurements of gas exchange may lead to improved management practices and decreased C loss from these fragile soils. This cooperative study was developed with the broad goal to determine the short-term effects of various tillage methods on the soil oxidation potentials and evolution of CO_2 (soil C loss) from the intensively tilled muck soils used for sugarcane production in the Florida Everglades (Morris et al., 2004; Gesch et al., 2007). As part of a larger study, the specific objective of this work was to determine the effect of Not Tilled (NT), tillage with a Harrell Switch

Plow (HSP), and wind speed on the soil CO_2 concentration in muck soils.

2. Methods and materials

This experiment was conducted on the Everglades Research and Extension Center (EREC) at Belle Glade, FL, USA of the University of Florida, Institute of Food and Agricultural Sciences (IFAS). The latitude and longitude of the field (field number 47 M 10 SE) is 26°39.07N, 80°38.05W, at 4.5 m above sea level. Sugarcane (*Saccharum* ssp.) is the major crop grown in the Everglades Agricultural Area (EAA) with a limited number of vegetable crops. The soil at the experimental site was a Histosol [Lauderhill soil (euic, hyperthermic, Lithic Haplosaprist)] representative of the large area of muck soils in south Florida. Soil classification in the muck soils is based on the depth to limestone bedrock. As soil subsidence continues, the soils classifications in the EAA are constantly transitioning from deeper to shallower classifications. The soil pH ranged from 5.9 to 6.3 as determined in a 2:1 water:moist soil mixture. The soil organic matter and total nitrogen were 87% and 2%, respectively with a rich, black appearance. The undisturbed bulk densities for the experimental sites range from 0.27 Mg m^{-3} in the surface to 0.46 Mg m^{-3} in the lower layers of the profile (Gesch et al., 2007). The loosened soil after HSP tillage could not be sampled with available equipment and the surface bulk density was estimated as 0.23 Mg m^{-3} based on an average 15 cm increase in the soil surface elevation following the plow. Average soil depth to bedrock in experimental plots was 64.7 cm (range 50–97 cm). The NT area was last tilled (‘‘blackened’’ as local jargon) using a heavy disc harrow (to about 15 cm) on Day Of Year (DOY) 2, 2002 to maintain a weed-free surface. The selected experimental treatments established in a north–south direction were NT, i.e., no recent tillage, and Harrell Switch Plow[2] (8-bottom Model 3608, LMC Mfg., Bainbridge, GA) that went 40–46 cm deep. The Harrell Switch Plow, a locally-derived term, allows the direction of the moldboard to hydraulically ‘‘switch’’ directions. Data were collected from 21 January (DOY 21) to noon on 25 January (DOY 25), 2002.

The HSP, pulled at a speed of 5 km h^{-1}, loosened the soil to an average 41-cm depth, i.e., below the sensing point of the infrared gas analyzer. The soil surface was used as a reference elevation for establishing the depth of the sensor housing within the plowed and NT soil profile. Typically the surface soil was black where there had been deep mixing with the previous tillage. The lighter brownish color ‘‘peat’’ layer was located immediately above the limestone bedrock that was used as a permanent reference elevation. The NT soil surface was ‘‘light colored’’ due to salt deposition following evaporation from previous rain.

The EREC weather station was located about 0.5 km northeast of the experimental site. The weather data included wind speed and wind direction at 6 m and 10 m above the soil surface, air temperature at 2 m, soil temperature at 1 cm and 10 cm under grass, total radiation, net radiation over a grassed area, photosynthetically active radiation and barometric pressure. The data were collected and recorded at 15-min intervals. The last significant rain before starting the experiment on DOY 21 was as follows: on DOY 14 there was 3 mm of precipitation followed by an additional 14 mm on DOY 15. Thus, 6 days prior to the experiment, there was a total of 17 mm of rainfall. On the day of tillage, the soil conditions were very dry in the top 10–12 cm, suggesting what rainfall had fallen had already evaporated as shown by Gesch et al. (2007).

The soil CO_2 concentration was measured with a Vaisala[2] miniaturized infrared gas analyzer, model GMP221, installed as shown schematically in Fig. 1. The infrared gas analyzers were factory calibrated with a range of 0–5% CO_2 or 50,000 μmol mol^{-1}. The infrared gas analyzer was mounted in a white PVC pipe housing (33 mm ID, 43 mm OD) with the dimensions shown in Fig. 2 along with a copper–constantan thermocouple to monitor temperature. The sensing area was accomplished by drilling 5–13 mm holes around the perimeter of the pipe to provide an opportunity for gas exchange. To prevent water-induced damage to the gas analyzer, these holes were covered with commercially available ‘‘Gore-Tex’’[2] fabric glued to the PVC housing that enabled gas diffusion into the housing, but prevented water flow. The sensor end of the analyzer was within 2 cm of this zone. The sensor depth identification was established as the centerline of these holes around the PVC pipe housing. Installation depth was 30 cm below the soil surface. The electrical cables were run through the rubber stopper in the top end of the PVC housing (Fig. 1) to a power supply (two 12 V batteries) and a Campbell Scientific[2] (CR23X) data acquisition system (DAS) and logged at 15-min intervals. The soil just covered the PVC housing surface to minimize any temperature gradients along the

[2] Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by USDA implies no approval of the product to the exclusion of others that may also be suitable.

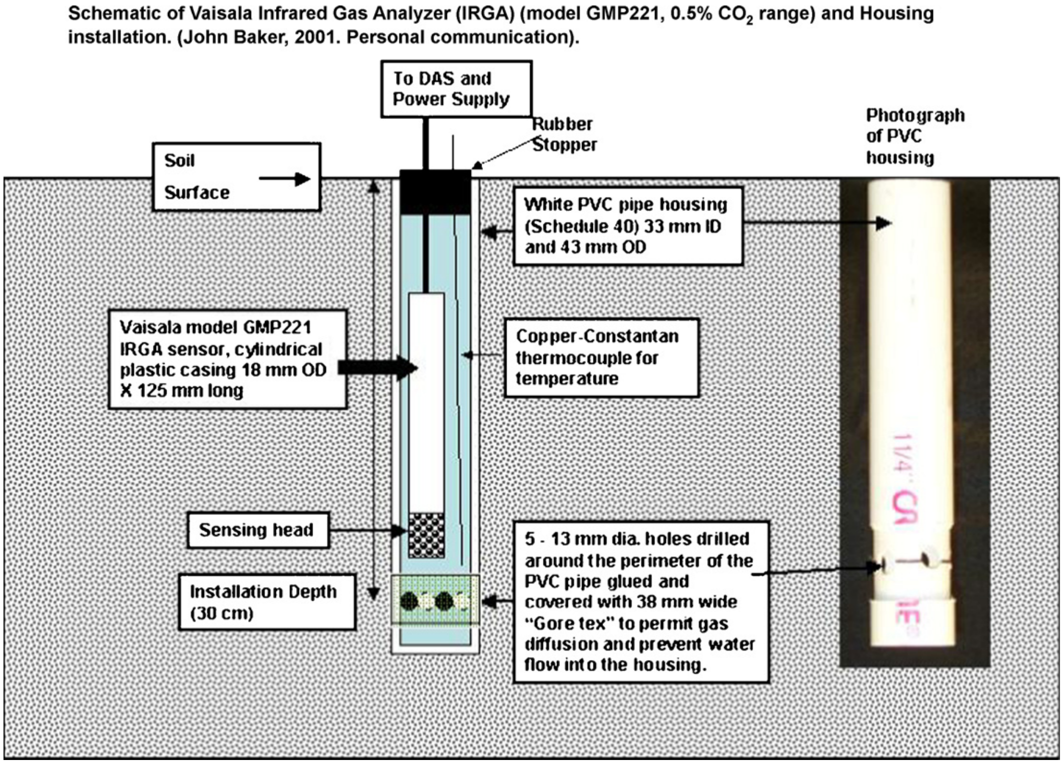

Fig. 1. Schematic of the Vaisala miniature infrared gas analyzer enclosed in the PVC pipe housing used to measure the CO_2 concentration at 30 cm.

wall of the PVC pipe. The time response for the Vaisala probe is less than 1 min without the Gore-Tex[2] fabric. However, in this configuration, the time response to reach 62% of the plateau value was about 2 h.

Two sensors were installed about 1 m from each other in the NT plot at 1400 h on DOY 21. Two more sensors were installed about 1 m from each other in the Harrell Switch Plow plot about 25 m south of the sensors in the NT plot at 0930 on DOY 22. These locations provided adequate fetch from three cardinal directions that was greater than 150 m. The west side was obstructed by 4-m tall photosynthetically-active sugarcane at a distance of about 15 m from a shallow surface ditch. Carbon dioxide sensors in their housing were installed using a soil probe (42 mm OD) as shown in Fig. 2. After the PVC housing for the infrared gas analyzer was installed using the soil probe, the soil was leveled and lightly tamped around the top of the tube to minimize any gas flow down the walls of the housing. The instruments were allowed to equilibrate under continuous data logging.

The air temperature recorded at 30 cm in the sensor housing surrounding the CO_2 probes using copper–constantan thermocouples and the DAS reference temperature were measured by the CR 23X data logger. The soil temperature at 30 cm was measured within 1 m of the CO_2 sensors using copper–constantan thermocouples in each treatment with a Campbell Scientific[2] CR10X logger. The soil temperature sensors directly in the soil were more stable and reflected the soil temperature adjacent to the CO_2 sensors.

3. Results and discussion

The weather data are summarized in Fig. 3 for the 5 days of the study. The air and soil temperatures from the weather station are shown in Fig. 3a. Maximum air temperature at 2-m height on DOY on 21 was 32 °C. However, in the remaining 4 days of the study, the maximum air temperature ranged between 27 °C and 28 °C near solar noon, and the temperature minimums ranged from 14 °C to 17 °C at the end of the experimental study. The soil temperature ranged from a maximum of 26 °C on the first day, but then ranged between 23 °C and 24 °C during the remaining 4 days. The soil temperature at 10 cm under grass at the weather station ranged from 20 °C to 23 °C during the same period.

The wind speed ranged from a low of 0 to a maximum of 6.5 m s^{-1} at 6 m in Fig. 3b. The wind

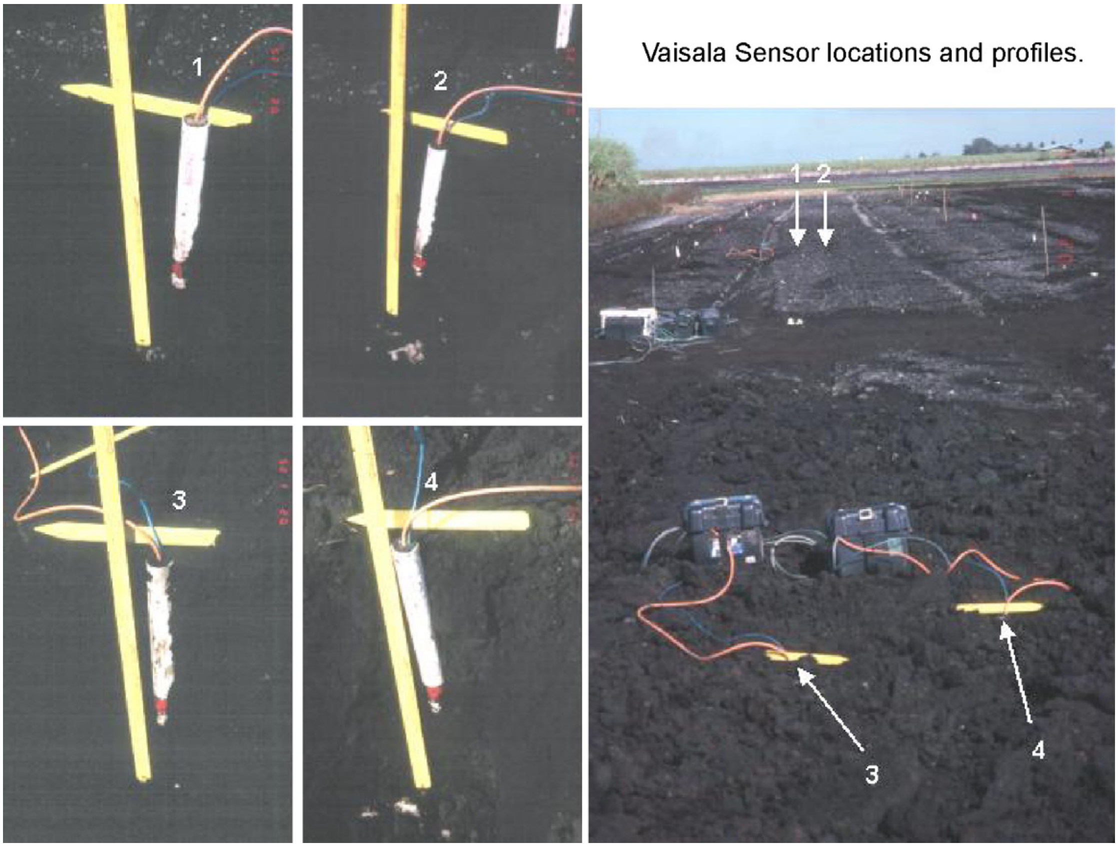

Fig. 2. Photograph of the field plots and housing with the miniature infrared gas analyzer sensors installed in the soil profile. Sensors 1 and 2 were installed in the No-Till plot and sensors 3 and 4 were installed in the Harrell Switch Plow plot.

direction was initially out of the north/northwest on DOY 22, and then changed to the southeast on DOYs 22, 23 and 24. There were two possible effects from the adjacent tall sugarcane. One was the modification of the westerly wind profile in close proximity to the sensor locations and the second was a possible shadow effect near sunset. Neither effect was evident in the data. During the 3 middle days of the study, the wind was out of the southeast over a large bare soil fetch area (>150–200 m) such that the sugarcane immediately west of the experimental site should have had a minimal effect on turbulence and aerodynamic forces operating on the gas exchange at the soil surface near the CO_2 sensors on both NT and HSP plots. On DOY 25, the wind was constantly changing direction from north around to the west and northwest at the end of the experiment.

The total incoming solar radiation, net radiation over grass, and photosynthetically active radiation all showed similar diurnal trends (Fig. 3c). The days were generally clear after the morning fog-lifted and heavy dew evaporated. Light cumulus clouds came through intermittently and resulted in somewhat lower radiation during the cloudy periods. Occasional clouds of black smoke from sugarcane burning upwind also affected the measured radiation. All 4 days of the study were consistent with respect to the amount of cloud cover during the study.

The barometric pressure and relative humidity are summarized in Fig. 3d. Barometric pressure showed a relatively narrow range in dynamic fluctuations, not related to diurnal trends. On DOY 21, the minimum pressure was 1017.2 mb and increased to a maximum of 1023.7 mb on DOY 22 to another low on DOY 24 of 1015.2 mb then a general increase to a maximum of 1021 mb on DOY 26. These barometric pressure fluctuations resulting from weather patterns changed as much as 3–4 mb within a day and a maximum of 8 mb (800 Pa) during the 4 days. The diurnal fluctuations in relative humidity followed the expected trends based on the solar radiation and airflow patterns. There was no diurnal variation or correlation of barometric pressure with the change in soil CO_2 concentration (defined as delta CO_2 later) at 30 cm in both the HSP and NT treatments (data not shown).

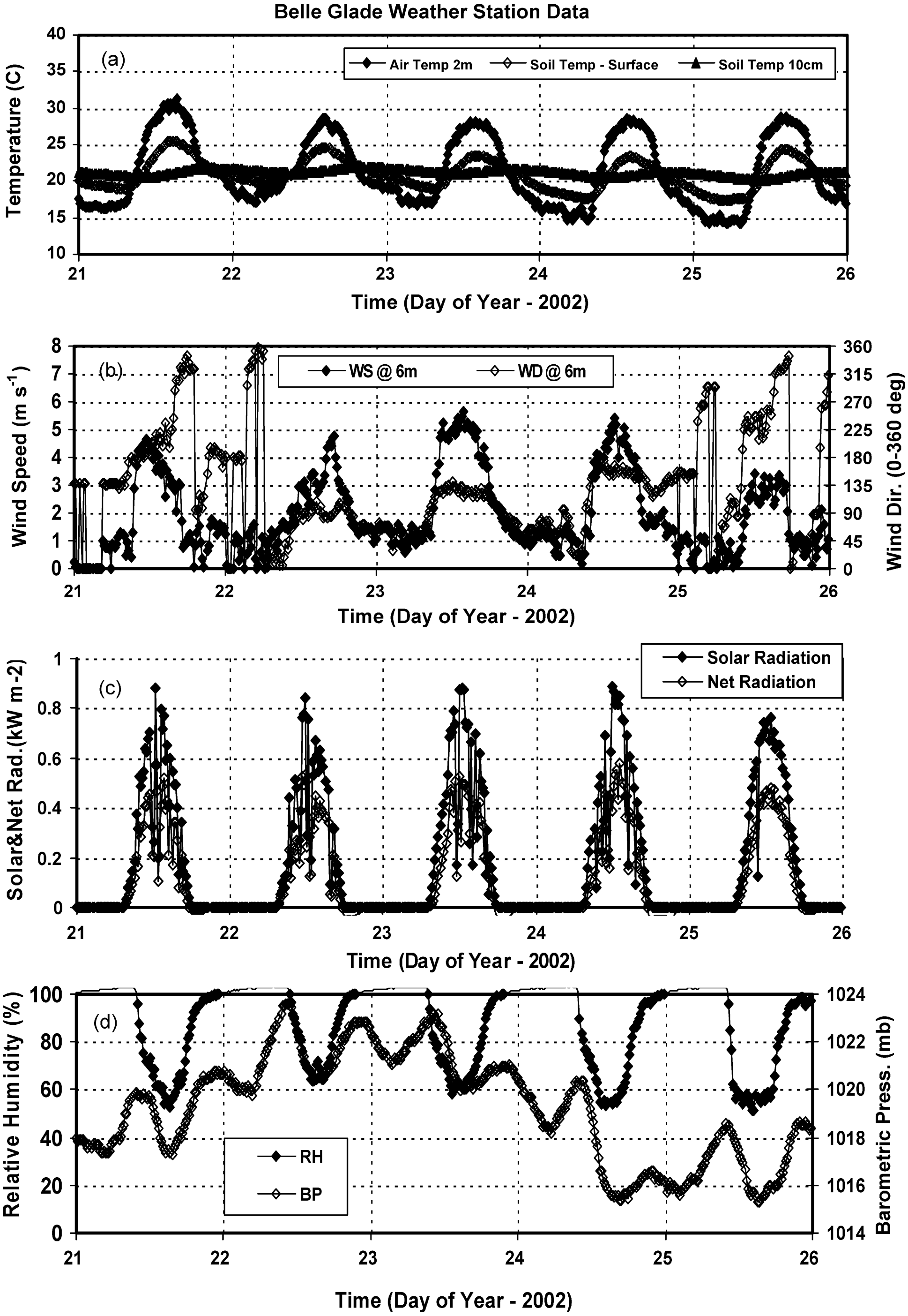

Fig. 3. Weather station data located 0.5 km northeast of the experimental site during the study period from DOY 21 to 26. (a) Air temperature at 2 m and soil temperatures, (b) wind speed and direction at 6 m, (c) incoming solar and net radiation, and (d) barometric pressure and relative humidity.

These results suggest barometric pressure changes had little effect on the soil CO_2 concentrations at 30 cm in agreement with Massman et al. (1997).

The time trends in soil CO_2 concentration at 30 cm below the soil surface in the NT and HSP plots are summarized in Fig. 4 along with the 6-m wind speed. Immediately after sensor insertion in the NT plot, the CO_2 concentration rapidly increased and within 8 h began to level off. There was nominal agreement between the two probes in NT that were located about

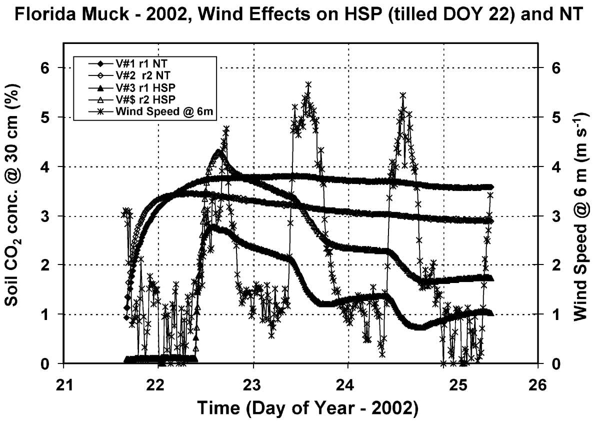

Fig. 4. Soil CO_2 concentration at 30 cm as a function of time in No-Till and Harrell Switch Plow plots along with wind speed measured at 6 m over the 4 days.

1 m apart. The maximum CO_2 concentration ranged from about 3.5% CO_2 for sensor 2 to a maximum of about 3.8% for sensor 1 in the NT plot. The CO_2 concentration showed a stable trend slowly declining with very subtle diurnal oscillations during the 4 days. Following installation of the CO_2 sensors in the HSP plots on DOY 22, there was a very rapid initial increase in the CO_2 concentration to as high as 4.3% CO_2 for sensor 4–2.8% for sensor 3. Again, there was nominal agreement between the two probes located about 1 m apart, suggesting spatial variability in muck soils. Immediately after reaching the initial peak CO_2 concentration, there was a precipitous decline in CO_2 concentration in the plowed plot on DOY 22 that appeared to be related to an increase in wind speed. The rate of decline in the CO_2 concentration during the night was lower and appeared to be related to lower wind speeds. At 0900 h on DOY 23, wind speed increased from about 1.5 m s^{-1} to about 4.5 m s^{-1}. There was another precipitous CO_2 decline in the plowed plot to lower concentrations that briefly leveled off or increased slightly during the night period. There was little change in CO_2 in the NT plot. During DOY 24, the CO_2 concentration showed another precipitous decline in the plowed plot as the wind speeds increased at about 1000 h. This response was repeated in the plowed plot the third day after installation, but at lower magnitudes out to the fourth day of the study when the CO_2 sensors were removed. The diurnal trends may be related to surface soil temperature fluctuations noted by Nakadai et al. (2002); however, soil temperatures measured at 30 cm next to the CO_2 sensors showed little diurnal variation (Fig. 5).

The dynamic trends and the differences in the magnitudes of the CO_2 concentrations were consistent among sensors. Carbon dioxide concentrations in the NT plot averaged about 3.3% while the plowed plot averaged 1.4% at the end of the study. Loosening the soil with the HSP resulted in a very rapid decline in CO_2 concentration as a result of "wind-induced" gas exchange from the plowed soil surface. The higher wind speeds during mid-day resulted in a more rapid loss of CO_2 from the HSP than from the NT plot. The results suggest that the tillage-induced change in soil properties (air porosity) enabled wind speed to enhance gas exchange and decrease soil CO_2 concentration at 30 cm. Wind affects gas exchange from these tilled muck soils with low pre-tillage bulk densities ranging from 0.3 Mg m^{-3} to 0.5 Mg m^{-3} and high soil air porosities associated with lower bulk density following tillage (Gesch et al., 2007). These bulk densities are presumably lower than those for the clay loam soil studied by Takle et al. (2004) and suggest that wind-induced dynamic pressure fluctuations were likely responsible for the rapid decrease in soil CO_2 concentration (Takle et al., 2003, 2004) rather than atmospheric barometric pressure changes suggested by Massman et al. (1997). The wind pumping dynamic pressure fluctuations appear to be more effective in CO_2 transport out of the porous soil rather than the relatively static barometric pressure. There appeared to be little relationship between barometric pressure and CO_2 concentration in either treatment.

The temperature recorded at 30 cm in the housing of the CO_2 probes is summarized in Fig. 5a along with the DAS reference temperature. The four thermocouples showed small diurnal fluctuations that ranged from about 21 °C to 25 °C depending on the location. The nominal diurnal fluctuations were a result of the temperatures being measured inside the sensor housing level with soil surface (possible radiation effect) and filled with air of different thermal characteristics. As a result, the diurnal fluctuations may not reflect the true soil temperatures at that depth, but give a general indication that the temperature was between 21 °C and 26 °C for all sensors. The actual soil temperature at 30 cm was measured within 1 m of the CO_2 sensors in each treatment summarized in Fig. 5b. These soil temperatures were more stable at 21–22 °C and more accurately reflect the soil conditions adjacent to the CO_2 sensors. The small soil temperature oscillations (1–2 °C) during mid-day reflect the DAS reference temperature sensor tracking air temperature (12.8 °C minimum, 33.5 °C maximum) inside the instrument housing that was exposed to direct radiation. Noteworthy was that the plowed soil temperature was typically 1–1.3 °C warmer than the NT treatment. The

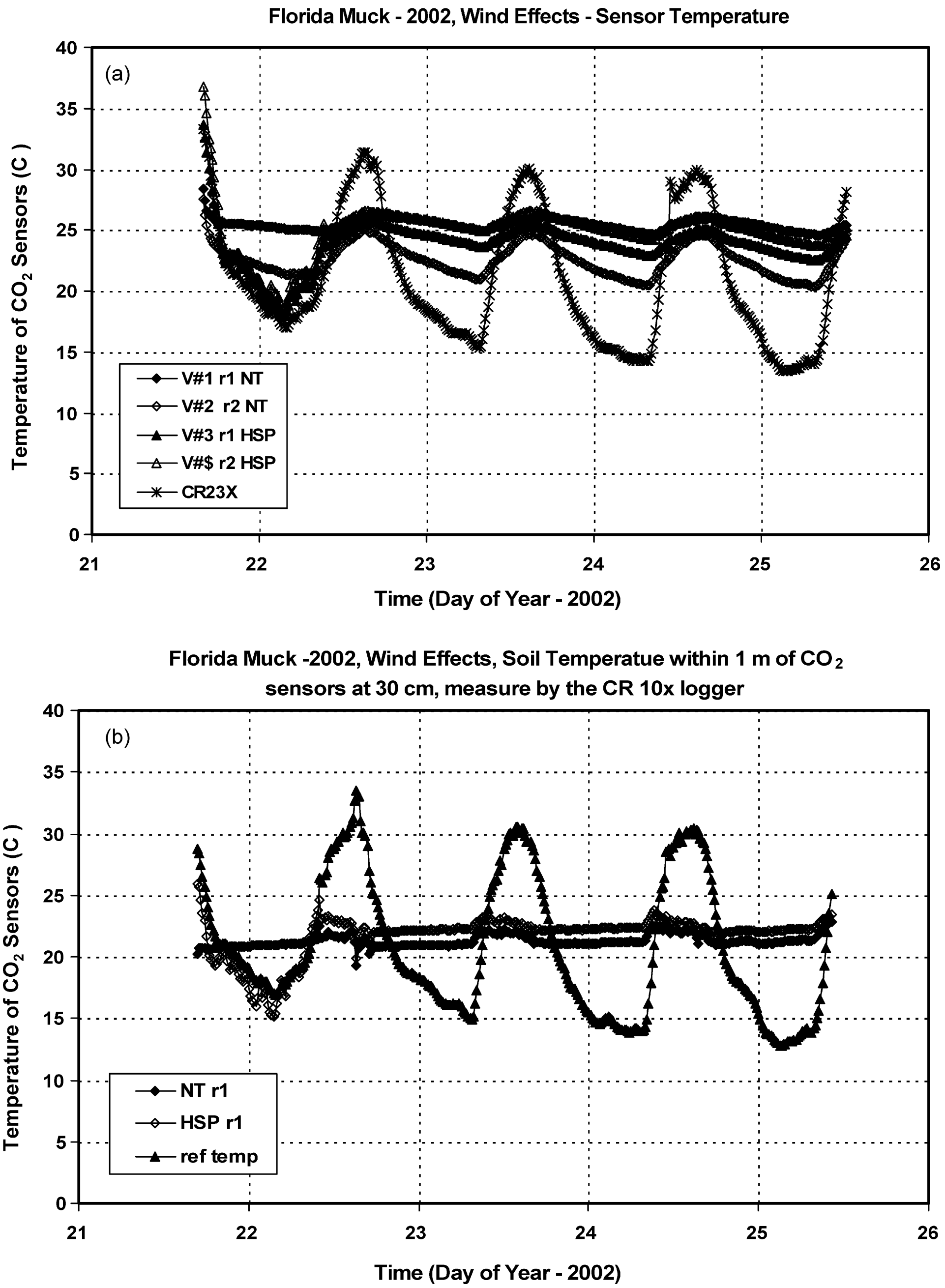

Fig. 5. (a) Sensor housing temperatures measured with the copper–constantan thermocouples associated with the Vaisala infrared gas analyzers with the DAS reference temperature measured by the CR 23X data logger for 4 days. (b) Soil temperatures measured with the copper–constantan thermocouples within 1 m of the Vaisala infrared gas analyzers along with the DAS reference temperature measured by the CR 10X data logger for 4 days.

larger diurnal temperature fluctuations in the CO_2 sensor housing suggest caution in interpreting the sensor temperature trends in this configuration; however, any effect on the CO_2 concentration at 30 cm appeared to be minimal. In fact, the CO_2 concentration in the plowed plot generally decreased with increasing soil temperature (Fig. 5b). The diurnal trends may be related to diurnal wind speed and surface soil temperature fluctuations noted by Nakadai et al. (2002); however, soil temperatures measured at 30 cm next to the CO_2 sensors had little diurnal variation suggesting a larger role of wind-induced changes in CO_2 concentration at depth.

In order to characterize the rate of change of soil CO_2 concentration at the 30 cm depth, we defined “delta

CO_2'' as the difference between the initial concentration and final concentration over a 15-min measurement interval. Thus, when delta CO_2 was >0, soil CO_2 concentration was decreasing with time. When delta CO_2 was <0, soil CO_2 concentration was increasing. Linear regression of ''delta CO_2'' with barometric pressure gave a nonsensical slight positive slope with a low R^2 in the HSP plot and a flat slope and low R^2 for the NT plot (data not shown). The delta CO_2 is plotted as a function of time for HSP plots in Fig. 6 along with the wind speed measured at 6 m. Prior to the tillage of the HSP plots, as shown in Fig. 6a, the CO_2 differences were small and oscillated around zero reflecting ambient concentrations when the sensors rested on the soil surface. However, after installation and reaching initial equilibrium, there was a delta CO_2 peak on DOY 22 followed with a decline (Fig. 6a). During the mid-day on DOYs 23 and 24, there were peaks in delta CO_2 that indicated rapid declines in CO_2 concentration that were related to increased wind speed. These results confirmed earlier observations of the precipitous declines in absolute concentration (Fig. 4). The delta CO_2 values were then regressed as a function of wind speed and summarized in Fig. 6b. Despite scatter in the data, there was a linear increase and a reasonable R^2 in delta CO_2 related to increasing wind speed. The CO_2 concentration after HSP tillage at 30 cm decreased with increasing wind speed.

The corresponding data for delta CO_2 as a function of time for the NT plot summarized in Fig. 7a reflect differences from the HSP treatment. Sensor 2 had more scatter (later determined to be pending electronic failure), than sensor 3 that may limit interpretation of the magnitudes of the change. The slightly higher surface bulk density and lower porosities of the NT plot (0.27 Mg m^{-3} for NT versus estimated 0.23 Mg m^{-3} for HSP plow) partially restricted gas flow out of the soil. As a result, the CO_2 concentration changes were much smaller in magnitude. Regression of delta CO_2 with wind speed yielded a flat slope and a poor

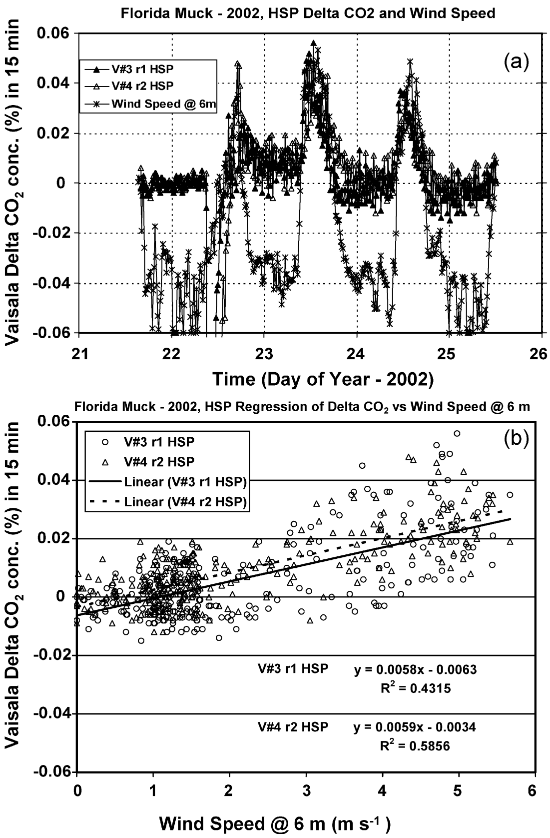

Fig. 6. (a) Rate of change of CO_2 concentrations at 30 cm in the Harrell Switch Plow plot and wind speed at 6 m. Delta CO_2 versus time as calculated, when the delta CO_2 is >0, CO_2 concentration is decreasing. When delta CO_2 is <0, CO_2 concentration is increasing, (b) delta CO_2 as a function of wind speed at 6 m fitted with linear regression.

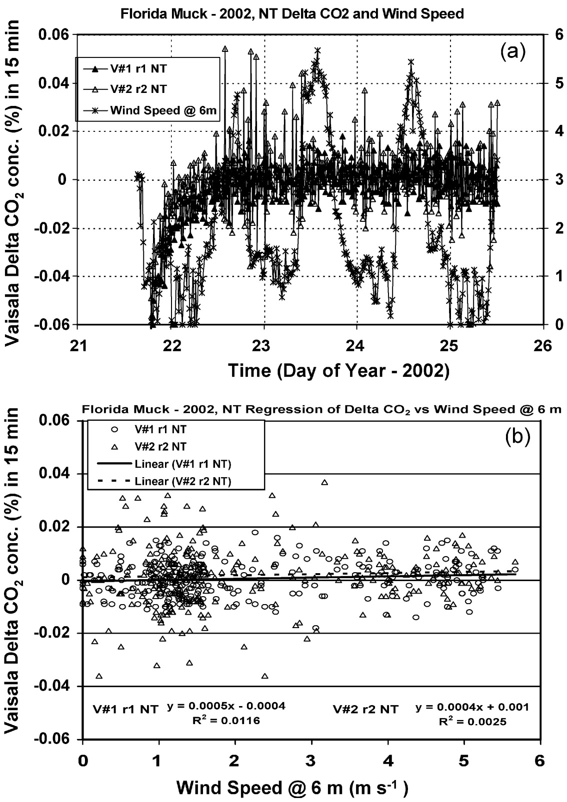

Fig. 7. (a) Rate of change of CO_2 concentrations at 30 cm in the No-Till plot and wind speed measured at 6 m. Delta CO_2 versus time as calculated, when the delta CO_2 is >0, CO_2 concentration is decreasing. When delta CO_2 is <0, CO_2 concentration is increasing, (b) delta CO_2 as a function of wind speed at 6 m fitted with linear regression.

correlation coefficient (Fig. 7b). The results suggest that leaving the soil in a NT system without any recent soil disturbance will minimize short-term CO_2 loss irrespective of the wind speed over the soil surface, at least up to 6.5 m s^{-1}.

The ambient CO_2 concentration determined the concentration gradient as the driving force for diffusion of CO_2 from 30 cm to the atmosphere. The soil CO_2 concentration was as high as 40,000 μmol mol^{-1} for sensor 4 (see Fig. 4). The initial ambient CO_2 concentration measured as part of an adjacent study (Gesch et al., 2007), ranged from a high of 626 μmol mol^{-1} at about 0600 h on DOY 23, as a result of nighttime respiration and low wind speed, to a low of about 384 μmol mol^{-1} during mid-afternoon when the adjacent canopy of sugarcane had maximum photosynthesis. Presumably the ambient concentration was even higher during the night. On DOY 22, the ambient CO_2 concentration only occasionally dropped below 400 μmol mol^{-1} which was most likely due to tillage-induced respiration in the immediate area. The results show limited dynamics of the ambient CO_2 concentration relative to the soil and how little the diffusion gradient might affect the CO_2 concentration in the soil especially in NT soil suggesting that wind-induced pressure forces were more effective in drawing CO_2 from a depth of 30 cm in the plowed plots (Takle et al., 2003, 2004).

Long-term studies in the muck soils have shown continued subsidence and a decline in soil C related to intensive tillage and drainage. The effect of wind and tillage on soil properties and its relation to gas exchange is very complex. The change in soil physical properties may partially explain the initial rapid loss of CO_2 from the soil surface. Soil subsidence is due to biological oxidation (respiration) that leads to transport of CO_2 from the soil into the atmosphere and is mainly driven by two mechanisms: diffusion and mass flow. The diffusive flux is driven by the concentration gradient between the soil and the atmosphere. The mass flow as a result of wind pumping is a result of convective pressure gradients that result from pressure differences due to air motion or flow over the porous soil matrix (Takle et al., 2003, 2004; Clarke and Waddington, 1991; Massman et al., 1997; Nazaroff, 1992). Both mechanisms are operating simultaneously in the field. The interaction of wind and soil properties on soil gas flux becomes even more critical when the soil is loosened by intensive tillage as demonstrated in this work and others (Ellert and Janzen, 1999; Rochette and Angers, 1999; Roberts and Chan, 1990; Reicosky and Lindstrom, 1993; Reicosky, 1997, 2002).

4. Summary and conclusions

To better understand factors causing soil subsidence in Florida muck soils, miniature infrared gas analyzers were installed at 30 cm in muck soil that was plowed or not recently tilled to evaluate the effect of tillage on soil CO_2 concentrations. Loosening the soil with the HSP to 41 cm resulted in a very rapid decline in soil CO_2 concentration at 30 cm as a result of "wind-induced" gas exchange from the soil surface. The higher wind speeds during mid-day resulted in more "dynamic pressure pumping" and a more rapid loss of CO_2 from the HSP than from the NT plot. The subtle diurnal trend in the NT plots was similar, but was much lower in magnitude. The tillage-induced change in the soil air porosity enabled wind speed to affect the gas exchange and soil CO_2 concentration at 30 cm, literally drawing the CO_2 out of the soil resulting in a rapid decline in the CO_2 concentration and likely a subsequent increase in the oxygen concentration. At the end of the study, CO_2 concentrations in the NT plots averaged about 3.3% CO_2 while the average concentration in the plowed plots was about 1.4%. The results suggest that the same wind pressure phenomena were active on the NT plot; however, the lower soil air porosity and the higher bulk density likely restricted the gas exchange. Longer running experiments would be needed to accurately quantify the long-term effects of wind speed on CO_2 loss from undisturbed soil. These results highlight wind-induced pressure and air mixing effects and support other findings of pressure effects with dynamic closed chambers used to quantify soil gas fluxes. Wind speed and associated aerodynamic pressure fluctuations can affect gas exchange from tilled soils, especially muck soils with low bulk densities and high soil air porosities.

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